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Managing drought risk in a changing climate: Irrigation and cultivar impacts on Michigan asparagus

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ABSTRACT

Increasing temperatures and rainfall variability in the Midwestern U.S. have spurred interest in strategies to reduce risks of heat and drought stress in traditionally rainfed crops including asparagus. A long-term field experiment was conducted on sandy soils in Western Michigan from 2010-17 to evaluate the effects of three levels of irrigation (none, overhead or sub-surface drip) and two asparagus cultivars (Guelph Millennium [GM] and Jersey Supreme [JS]) for reducing these risks. Overhead irrigation during the fern growth period resulted in cumulative yield improvements of 10% for GM during the 2012-17 growing seasons, with the largest yield benefits (21%) occurring in 2012, following hot, dry conditions the previous summer. In contrast, cumulative yields of JS were unaffected by irrigation, and yield reductions of 13% due to irrigation were observed in 2017, following wet conditions the previous late summer and fall. Estimates of cultivar water-use by depth suggest that JS was better able to tolerate drought due to a deeper root system compared to GM. However, our results suggest that JS may also be more sensitive than GM to excessive soil moisture during fall senescence. Yield response did not vary with delivery system, but sub-surface drip used less water than overhead irrigation. These results demonstrate the important role of both genetics and management practices in mitigating drought risk.

1. Introduction

Increasing summer temperatures and rainfall variability have been observed in the Great Lakes region and climate models predict continuation of these trends (Villarini et al., 2011; Pryor et al., 2014). According to Pryor et al. (2014), the average Midwest air temperature increased by more than 0.80 °C between 1900 and 2010, with an acceleration of warming observed since 1950. Trends in Midwest drought severity and duration depend on the geographical area, timescale, and timing evaluated. For example, drought stress and severity in the Midwest reportedly declined between 1916–2007 (Mishra and Cherkauer, 2010). In contrast, Dai et al. (2016) report increasing temperatures and declining rainfall in the late-growing season between 1980–2013. Regional climate models predict higher average levels of spring precipitation, reductions in average summer precipitation of approximately 8% by 2050 (Pryor et al., 2013), and increases in the number of days without precipitation (Pryor et al., 2014). Observed increases in the variability and intensity of rainfall (Villarini et al., 2011) are also expected to increase (Rahmstorf and Coumou, 2011; Pryor et al., 2014).

Projected increases in summer temperatures and reductions in summer rainfall suggest that many important agricultural crops in the Midwest—including asparagus—may experience increases in heat and drought stress in the coming decades that threaten their economic viability. The US asparagus industry has a value of approximately $73 million per year, with Michigan accounting for the largest acreage of any state (USDA-NASS, 2018). High temperatures coupled with low precipitation have negatively impacted asparagus quality and yield in several production regions with climates similar to that of Michigan. During harvest, high temperatures reduce spear quality and increase the rate of spear growth, making it difficult for timely harvest given limited labor availability. For example, Heißner et al. (2006) showed that for some white asparagus cultivars, the percentage of open tips increased from 0 to 20% or more as soil temperatures increased from 20 to 25 °C. Similarly, in green asparagus, reduced soil and air temperatures were associated with a lower percentage of open tips (Brainard et al., 2018). Although asparagus is deep-rooted and relatively drought tolerant, soil water content during fern growth is an important

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determinant of crop yields (Drost and Wilcox-Lee, 1997; Hartman 1981), and drought stress during fern growth can limit the capacity of plants to produce the soluble carbohydrates in storage roots necessary for high yields in subsequent seasons (Drost and Wilcox-Lee, 1997). Stressed plants may also be susceptible to fungal diseases including *Fusarium* (Morrison et al., 2011) and *Phytophthora* (Saude et al., 2008).

Investment in irrigation systems is one potentially valuable approach for reducing risks associated with predicted increases in drought. Historically, Michigan asparagus has not been irrigated. However, irrigation trials have demonstrated improved yields in many parts of the world, including rain-fed climates similar to that of Michigan (Hartmann, 1981; Rolbiecki and Rolbiecki, 2007; Zinkernagel and Kahlen, 2015). For example, Rolbiecki and Rolbiecki (2007) observed yield improvements of over 30% with many cultivars in Poland. In Germany, irrigation resulted in increased spear number and yield on sandy soils (Hartmann (1981, 1996); Zinkernagel and Kahlen, 2015). However, in some cases, excessive moisture can exacerbate fungal pathogens like *Phytophthora asparagi* (Saude et al., 2008) or cause excessive fern growth, which may reduce assimilate accumulation and subsequent yields (Wilson et al., 1996).

Beyond its direct effects, irrigation may also indirectly benefit cropping systems by creating opportunities for valuable complementary practices including cover-cropping and fertigation. For example, in irrigated asparagus production systems, cover crops growing below the fern canopy may be established with reduced risk of competition for water with the asparagus crop (Brainard et al., 2012). If competition for water is minimized, these living mulches may suppress weeds, protect soils from erosion (Paine, 1995; Brainard et al., 2012) and improve nutrient retention and recycling (Paschold and Artelt, 1995) without adversely affecting crop growth. Irrigation may also be used to apply, activate, or protect fertilizers and pesticides, thereby reducing input costs and losses to the environment (Threadgill, 1985).

Several different irrigation systems are available to growers including overhead, surface drip and sub-surface drip, and the choice of system can impact water use efficiency, crop response, efficacy of complementary practices and profitability (Camp, 1998; Sterret et al., 1990). In general, yields of many field and horticultural crops are similar to, or better with subsurface drip irrigation compared to overhead or furrow irrigation, with improved water use efficiency (Camp, 1998). For example, in one of the few studies comparing irrigation systems for asparagus, Sterret et al. (1990) found that in some years, yields of asparagus were improved and water-use reduced with sub surface drip irrigation compared to overhead sprinklers. In Peruvian asparagus production systems, it is estimated that drip irrigation systems use about 63% as much water as flood irrigation while maintaining crop yields (Schwarz et al., 2016). In addition, under drip irrigation, fertigation can be used to target agrichemicals directly to the root zone, thereby lowering input costs and minimizing losses through leaching and volatilization. By minimizing soil surface and leaf moisture, drip systems may also reduce the incidence of foliar diseases (Rotem and Palti, 1969) and weeds (Grattan et al., 1988). However, for large scale production, overhead irrigation systems are often less expensive and more flexible than subsurface drip and can be used to reduce heat stress through evaporative cooling (Brainard et al., 2018), to facilitate herbicide activation and cover crop establishment (Brainard et al., 2012), and to reduce soil erosion (Tibke, 1988) and the damaging effects of wind-blown soil (Hodges and Brandle, 2006).

Crop cultivars vary in their tolerance to heat and drought stress, and identification of traits associated with that tolerance may facilitate efforts to breed more resilient cultivars. Drought tolerance may be determined in part by traits related to stomatal regulation (Schaller and Paschold, 2009; Cattivelli et al., 2008), phenology (Richards, 2006) or root depth and morphology (Hund et al., 2009; Lopez et al., 2017). In asparagus, several studies have documented variation in cultivar response to irrigation and tolerance to drought (Hartmann, 1981, 1996; Rolbiecki and Rolbiecki, 2007; Wilson et al., 1996; Schaller and Paschold, 2009), but the basis for this variation is often unclear. In controlled greenhouse studies, Schaller and Paschold (2009) found evidence that the drought tolerant cultivar “Grolim” had more sensitive stomatal regulation in response to water deficit and hence greater tolerance to drought than the cultivar “Gijnlim”. However, drought tolerance is often the result of a complex combination of traits that entail tradeoffs which must be understood in order to develop new cultivars with improved performance in dry environments (Cattivelli et al., 2008).

The primary objectives of our research were to 1) characterize historic changes in water deficits occurring during peak fern growth in western Michigan, one of the primary asparagus producing regions of the US; 2) evaluate the potential importance of irrigation and cultivar selection for managing drought stress in asparagus; 3) evaluate cultivar differences in soil water use patterns at different depths and 4) evaluate the relative impacts of different irrigation delivery systems (sub-surface drip versus overhead) on yield and water use. We hypothesized that 1) irrigation during fern growth would improve asparagus yields; 2) drought tolerance, and hence the benefits of irrigation would vary by cultivar; 3) variation in cultivar response to drought would be associated with differences in soil water-use patterns; and 4) sub-surface drip irrigation would provide equivalent yield improvements to overhead, while reducing water requirements. Overall, we anticipated that combinations of irrigation and cultivar choice would reduce the risks associated with drought stress in Michigan production systems.

2. Materials and methods

2.1. Historic climate

To characterize historic water deficits of greatest relevance for asparagus production, we used reference potential transpiration (rPET) and rainfall data from the Hart, MI (43.7366 Lat.; -86.3594 deg Long) Enviro-weather Network station (MSU, 2018) located in the center of Michigan’s primary asparagus production region. rPET was calculated using using the FAO Penman Monteith equation (Allen et al., 1998) from temperature, humidty, wind speed and irradiance data available from the Hart station since 1997. We calculated the potential water deficit (PWD) as the difference between rPET and rainfall during each month from June –September, as well as for the peak fern growth period from July-August. During July and August, the asparagus canopy is typically closed, cladophylls are fully expanded, and crop coefficients typically range from 0.7 to 1.0 (Paschold et al., 2003).

2.2. Site characteristics and experimental design

A field experiment was established in Oceana County, western Michigan in 2010. Six experimental treatments were examined consisting of all combinations of two factors: 1) “Irrigation system” with three levels (none, overhead, and sub-surface drip) and 2) asparagus cultivar with two levels (“Jersey Supreme” [JS] and “Guelph Millennium” [GM]). The experimental design was a split-plot design with irrigation system as the main plot factor, and cultivar as the subplot factor. Main plots were arranged in a randomized complete block design with 4 replications, and subplots randomly assigned to either half of each main plot. Main plots measured 6.1 x 36.4 m with four rows of asparagus spaced 1.5 m apart. Subplots were 6.1 x 18.2 m. Data were collected from the inside two rows of each plot to minimize edge effects.

The soil type was representative of Michigan asparagus production: a well-drained Spinks loamy fine sand (86% sand, 8% clay, and 3% silt) with volumetric soil moisture content in the top 60 cm of approximately 11.5% at field capacity and 3.3% at the permanent wilting point (NRCS, 2017). The experimental area had no reported history of previous asparagus production and had been either fallowed or cover-cropped for several years prior to planting. Soils sampled from the experimental

area had a mean pH of 6.7, soil organic matter content of 1.2%, and K, P, Ca and Mg concentrations of 81, 120, 439 and 84 ppm, respectively.

2.3. Trial establishment and maintenance

On 17 May 2010, one-year old crowns were planted at a density of 36,889 ha^{-1} at approximately 23 cm depth in furrows spaced 1.5 m between rows. The weight of GM crowns was less than that of JS but both cultivars appeared un-desiccated and disease free. Netafim Uniram tubing with 45 cm emitter spacing and 1.59 L per hour output was placed below the crowns in-furrow in sub-surface drip irrigation plots. Furrows were filled in slowly to hill over crowns with several cultivations during June and July as plants became established. Asparagus was managed in accordance with standard grower practice with annual applications of herbicides, insecticides and fungicides applied as needed to control weeds, insects (including asparagus miner and asparagus beetle), and foliar diseases (including purple spot and rust) (Hausbeck et al., 2017). Fertilization consisted of initial applications of 50, 50 and 135 kg/ha, of N, P and K, respectively, followed by annual applications of 90, 157, 20 and 2.5 kg ha^{-1} of N, K, S and B in subsequent years. The only management practice that varied by treatment was irrigation system as described below.

2.4. Moisture monitoring and irrigation

During the 2011–2016 growing seasons, soil volumetric water content (VWC) was monitored using the Diviner 2000 system (Sentek, Stepney, AU) which estimates VWC based on measurements of soil capacitance. In 2010, one meter long specialized PVC tubes were hand-augured into each plot to record moisture at 10-cm intervals to a depth of 90 cm. In 2011 and 2012, readings were conducted on a weekly basis throughout the fern growth period, with additional readings taken before and after each irrigation event. In subsequent years, readings were taken at 1–2 wk intervals. Mean VWC to a depth of 60 cm was used to schedule irrigation. Unreliably low VWC readings (VWC < 2%) were excluded from analysis. These occurred primarily at the 10 cm depth in 2011 and 2012 due to occasional poor soil contact with sensor tubes. Irrigation was initiated when VWC declined to 25–50% of available water (5.4–7.4% VWC) and was applied to replenish soil moisture to 75–100% of available water (9.5–11.5% VWC). Overhead irrigation was applied through Nelson Orbitors (Model R-10, Walla Walla, WA) with road guard blinders with an overlapping, alternating 5.8 m radius, semi-circular spray pattern from 1.5 m PVC risers.

2.5. Change in VWC by depth

To gain insight into cultivar differences in water use by soil depth, the change in VWC during selected dry periods was evaluated in un-irrigated treatments at 10 cm increments to a depth of 90 cm. For this analysis, we selected 1–2 week intervals during the fern growth period from late June to early August based on availability of VWC data, absence of rainfall, and initial VWC between 50–75% available water. These conditions were chosen in order to eliminate changes in VWC due to precipitation, and to minimize changes due to drainage. For each dry period, daily water loss from each soil depth was calculated by dividing total water loss from that depth by the number of days.

2.6. Fern evaluation

Fern biomass samples were collected after first frost in November of each year from 2011–2017. In all years, stems were clipped at the soil surface, weighed fresh in the field, and converted to dry weights based on the dry:fresh weight ratio of an approximately 1 kg sub-sample. The fresh weight sampling unit varied somewhat between years: In 2011 and 2012, 25 stems were sampled from each plot to determine fresh weights, and converted to kg/ha units based on stem density counts; in other years, fern fresh weights were taken from all stems from either three (2013, 2014 and 2016) or six subsamples (2015 and 2017) consisting of 1 m of row from the center two rows of each plot.

During drought conditions in 2011, several additional measurements were taken to characterize drought effects on fern growth. On 8 August, stems were categorized and counted from two 1 m row sections per plot as either: “mature” (stems with cladophylls), “new” (recently emerging stems without cladophylls) and “dead” (stems with no green tissue). To non-destructively measure fern development, light interception was measured with a portable PAR-sensing bar (Lightscout 6 quantum bar, Spectrum Technologies, Aurora, IL) between 11 A M and 1 PM under clear skies on 19 Aug, 6 Sept and 4 October. In each plot, one reading was taken above the canopy and five readings taken below the canopy at approximately 30 cm above ground level with light interception calculated as:

$$LI = 100 - (PARb/PARa)*100 \quad (1)$$

Where PARb is the average of the 5 below-canopy measurements and PARa is the above canopy measurement. On 4 October 2011, prior to cladophyll sensescence, all stems from 5 crowns per plot were cut at the soil surface, dried, separated into cladophyll and non-cladophyll tissue and weighed.

2.7. Yield and quality assessment

Yields were determined from the center two rows of each sub-plot during the 2012-17 harvest seasons (late April-early June). Harvests occurred every 1–2 days, for a total of 13 harvests in 2012 and 20 to 23 harvests each season thereafter. Harvest was done by hand, using the snapping method common in Michigan. Spears were harvested at 15–25 cm length. Cumulative fresh weight of marketable yield for each year was calculated for analysis. In addition, spear quality was assessed from all spears on two harvest dates in 2012 (14 May and 24 May), classifying spears into the following size grades by diameter at the base: Small (between 7.9 and 12.7 mm), Regular (12.7 to 17.5 mm) and Jumbo (greater than 17.5 mm). The total number and fresh weight of spears in each size grade was evaluated, and mean weight per spear calculated by dividing the total number of spears by their total weight for each size category.

2.8. Statistical analysis

For each year of the study, the fixed effects of irrigation (none, overhead or drip) and cultivar (GM or JS) and their interactions on VWC, asparagus stem number, shoot dry weight, yield and quality measures were analyzed using PROC MIXED procedures in SAS (SAS Institute, 2009) with block and irrigation*block interaction as random effects. To improve assumptions of normality and homogeneity of residuals, stem number data was either log- or square root-transformed and cladophyll data log-transformed prior to analysis. All other responses did not require transformation. Because changes in VWC during dry down periods (see Section 2.4) were evaluated only in cultivar subplots within unirrigated treatments, our design for this response simplified to a randomized complete block design with 4 replicates (blocks). Therefore, only the fixed effect of cultivar was included in the model, with block treated as a random effect.

3. Results and discussion

3.1. Rainfall and potential evapotranspiration

Historic potential water deficits (PWD) during peak fern growth (July-Aug) in Hart, MI increased between 1997 and 2017 (Fig. 1). Although large annual variations in PWD occurred, linear regression of PWD against year demonstrate an overall increase in PWD during peak

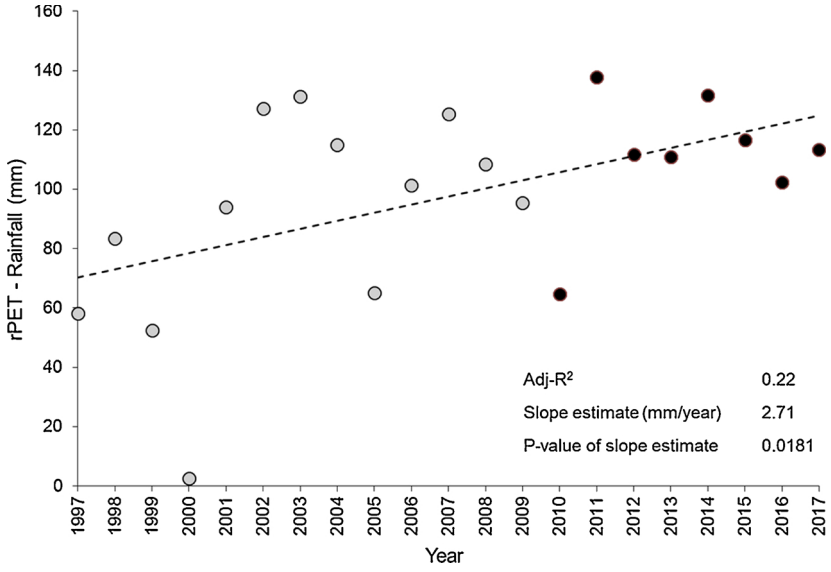

Fig. 1. Potential water deficit (reference Potential evapotranspiration [rPET] – rainfall) in Hart, MI during peak fern growth (July and August), 1997-2017. Black dots indicate water deficits during the irrigation study period. Grey dots indicate water deficits prior to initiation of the study. The dotted line is the best fit linear regression for which parameter estimates are presented.

Table 1
Monthly rainfall, reference potential evapotranspiration (rPET) and potential water deficit (rPET - rainfall), Hart, Michgian, 2010-17.

	Rainfall					rPET[1]					Potential water deficit (rPET - rainfall)				
Year	June	July	August	September	Peak Fern Period (July-Aug)	June	July	August	September	Peak Fern Period (July-Aug)	June	July	August	September	Peak Fern Period (July-Aug)
2010	128	108	78	74	186	116	138	114	72	251	−12	30	35	−2	65
2011	107	64	47	67	111	116	139	109	75	249	9	75	62	8	138
2012	62	122	29	53	151	155	156	107	87	263	93	34	78	34	112
2013	39	63	57	60	120	118	128	103	82	231	80	65	46	21	111
2014	107	29	49	53	78	100	123	86	59	209	−7	94	37	6	132
2015	114	72	49	57	121	115	138	99	84	237	1	66	50	28	117
2016	53	112	34	141	145	136	137	111	84	248	83	26	77	−56	102
2017	111	64	62	20	126	130	136	103	95	239	19	72	41	75	113
2010-2017	90	79	51	66	130	123	137	104	80	241	33	58	53	14	111
1997-2009	67	65	78	61	143	126	133	99	82	232	59	68	21	20	89
20 year avg	76	70	68	65	138	125	134	101	80	235	49	64	33	15	98

1rPET = reference potential evapotranspiration.

fern growth of approximately 54 mm since 1997, with average annual increases of 2.71 mm year^{-1} (P-value 0.018). This increase in PWD reflects a combination of declining rainfall and increasing rates of rPET during July and August (Table 1). It should be noted however, that no comparable trends were observed for June (harvest and early fern growth period) or September (onset of fern senescence). These results are consistent with regional climate models for the Midwest, which project increased spring precipitation, but reductions in average summer precipitation of approximately 8% by 2050 (Pryor et al., 2013), as well as increases in summer temperatures (Pryor et al., 2014).

Consistent with the long-term trends, PWD during the irrigation experiment (2010–17) were generally higher than the 20 year average (Fig. 1; Table 1). During peak fern growth and irrigation testing (July-Aug), mean precipitation from 2010-17 was 130 mm, ranging from 78 mm (2014) to 186 mm (2010). Preciptitation during this period was slightly lower than the 20 year average of 138 mm. In contrast, fern-period reference potential evapotranspiration (rPET) was higher than the 20 year average (235 mm), ranging from 209 mm (2014) to 251 mm (2012) (Table 1). The potential water deficit (rPET – rainfall) during the fern growth period was greatest in 2011 (138 mm) and 2014 (132 mm).

3.2. Irrigation and soil moisture

Soil VWC varied considerably both across and within years (Fig. 2; lines), based in part on differences in the quantity and timing of rainfall and irrigation events (Fig. 2; bars). As expected, years with greatest potential water deficits (Fig. 1)—2011 and 2014—also generally had the most prolonged periods of low soil moisture (VWC < 25% available) (Fig. 2A and D). In contrast, relatively few periods of low VWC occurred in 2015 and 2016 (Fig. 2E and F).

The number of irrigation events used to maintain VWC > 25% available in irrigated treatments ranged from three in 2015 and 2016 to seven in 2011 (Fig. 1A–F, gray bars). Both irrigated treatments had significantly greater VWC than the unirrigated control ($P < 0.05$) for extended periods ranging from late July until late August in 2011, 2013, 2014 and 2015. In contrast, differences in VWC in 2012 and 2016 were limited primarily to early July. In 2015, the irrigation event that occurred in early August was followed by multiple rainfall events, resulting in moisture levels near field capacity going into September.

3.3. Fern response to irrigation

Final fern dry weight in late fall differed by cultivar, but not by irrigation system (Table 2). Detailed fern data collection from 2011 suggests that the lack of detected irrigation effects on final fern biomass may have been due in part to large variability in fern biomass data at the final sampling date, and to the loss of cladophylls that occurred before that time. In 2011, fern dry weight sampled on 4 October, prior

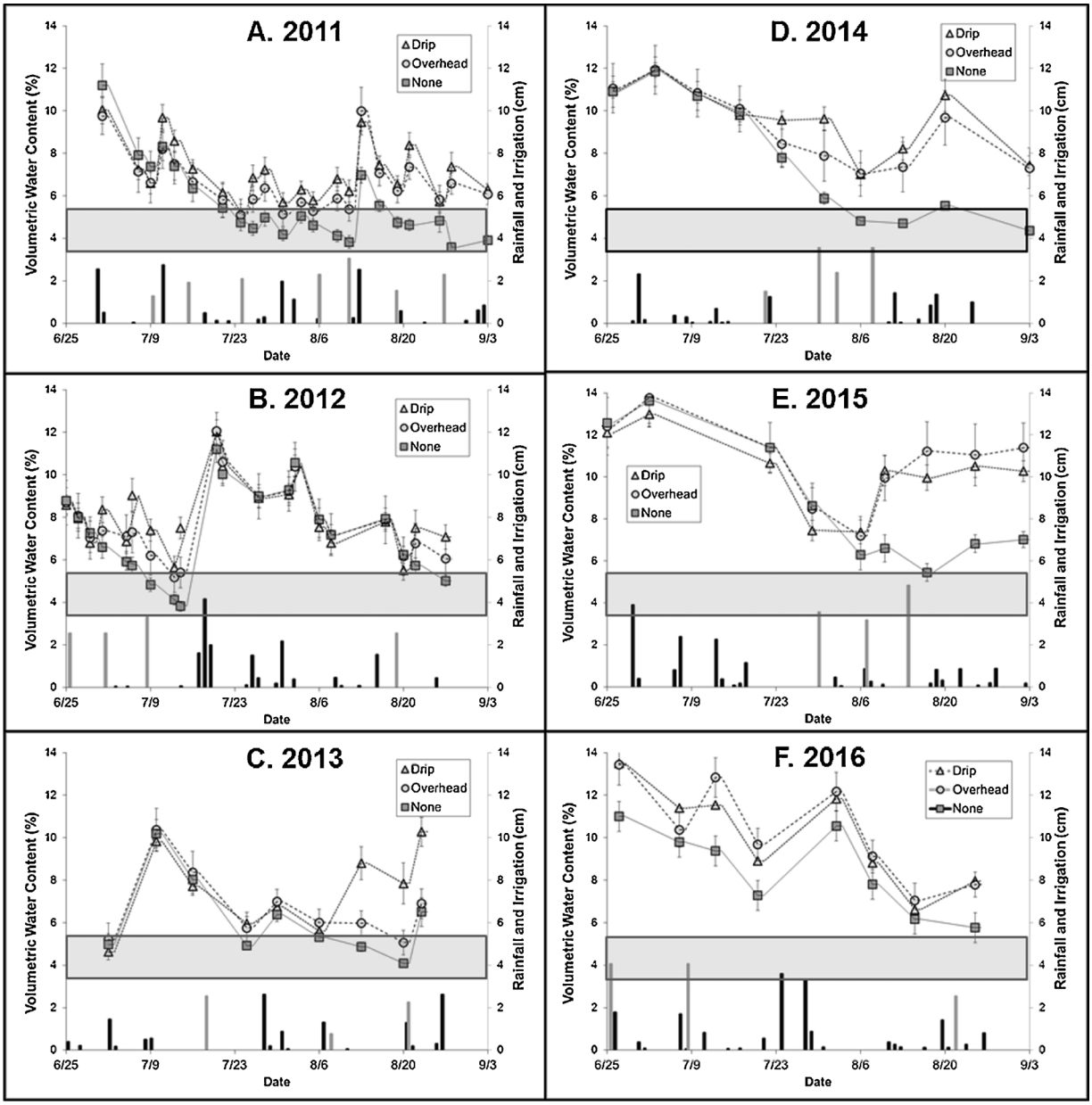

Fig. 2. Rainfall (grey bars), irrigation (black bars) and mean (± standard error) volumetric water content (VWC) to 60 cm (lines) for unirrigated (square), drip irrigated (triangles) and overhead irrigated (circle) treatments, from 2011 to 2016 (A–F). Data are combined for both cultivars. Shaded rectangles are provided for reference to represent VWC from the permanent wilting point, to 25% plant available water.

to cladophyll drop, revealed 45% higher cladophyll dry weight in drip irrigated versus unirrigated treatments (Table 3). Following cladophyll drop at the 11 November sampling date, differences in fern shoot weight were no longer significant (Table 2)). Light interception from developing fern—an indirect measurement of fern leaf area—was also higher in irrigated treatments compared to the un-irrigated treatments

Table 2
Effects of cultivar and irrigation on fern dry weight, 2011–2017. Cultivars included Jersey Supreme (JS) and Guelph Millennium (GM). Irrigation included none, overhead or sub-surface drip.

	2011	2012	2013	2014	2015	2016	2017
	T/ha						
Jersey Supreme	2.70 a	2.79 a	2.80 a	2.82 a	2.65 b	2.29	3.23
Guelph Millennium	2.15 b	2.39 b	2.20 b	2.24 b	3.32 a	2.36	3.15
	P-value						
Cultivar	0.0207	0.0225	0.0009	< 0.0001	0.0032	NS	NS
Irrigation	NS	NS	NS	NS	NS	NS	NS
Cultivar x Irrigation	NS	NS	NS	NS	NS	NS	NS

1Within each column, different letters indicate signficant difference at $P < 0.05$.

Table 3
Fern stem number, light interception of fern, and fern dry weight, 2011. Cultivars included Jersey Supreme (JS) and Guelph Millennium (GM). Irrigation included none, overhead or sub-surface drip.

	Stem Number (11-Aug)				Light interception			Fern dry weight 04-Oct		
Treatment	Total #/m-row	New	Mature	Dead	19-Aug %	06-Sep	04-Oct	Cladophyl T/ha	Stem	Total
Cultivar main effect										
Jersey Supreme	35.1 a	2.5	30.8	1.7 (a)	86.1 a	85.4 a	79.5 a	0.36	2.0	2.3
Guelph Millennium	22.3 b	1.5	19.9	0.8 (b)	75.2 b	77.1 b	72.8 b	0.30	1.7	2.0
Irrigation main effect										
None	28.6	1.6	25.4	1.6	77.2 (b)	74.7 b	69.7 (b)	0.25 (b)	1.6	1.9
Drip	28.9	0.9	26.0	2.0	82.7 (a)	84.1 a	80.0 (a)	0.39 (a)	1.9	2.3
Overhead	28.5	1.3	24.7	2.6	82.1 (ab)	85.0 a	78.7 (a)	0.35 (ab)	2.0	2.3
Cultivar*irrigation										
Jersey Supreme										
None	35.3	2.0	31.3 ab	2.0	82.0	78.0	72.2	0.24	1.8 abc	2.0 ab
Drip	38.0	2.5	34.3 a	1.3	90.2	89.2	84.9	0.46	2.4 a	2.8 a
Overhead	32.0	3.1	27.0 bc	1.9	86.1	89.0	80.9	0.37	1.7 abc	2.1 ab
Guelph Millennium										
None	21.9	1.1	19.6 d	1.1	72.4	71.4	66.6	0.26	1.5 bc	1.7 b
Drip	19.9	1.5	17.8 d	0.6	75.2	78.9	75.2	0.32	1.4 c	1.7 b
Overhead	25.0	2.0	22.4 cd	0.6	78.2	81.1	76.4	0.33	2.3 ab	2.6 ab
ANOVA										
Cultivar	< 0.001	NS	< 0.001	0.063	< 0.001	0.001	0.009	NS	NS	NS
Irrigation	NS	NS	NS	NS	0.078	0.019	0.053	0.081	NS	NS
Cultivar x Irrigation	0.066	NS	0.007	NS	NS	NS	NS	NS	0.026	0.034

1Within each column, different letters indicate signficant difference at $P < 0.05$. Letters in parentheses are used to indicacte differences at $0.05 < p < 0.10$.

in 2011 (Table 3). Specifically, fern light interception was 7, 13 and 14% higher in irrigated compared to unirrigated treatments at the Aug, Sept and Oct sampling dates, respectively.

Previous studies have shown increases in fern growth with irrigation, but these responses have not always been correlated with improvements in yield. For example, Wilson et al. (1996) recorded increases in fern bioimass of 29% following high levels of irrigation during a hot dry season, but yields the following year were reduced by 54%. On the other hand, Sterret et al. (1990) reported increases in fern stem number, diameter and height in response to irrigation, as well as subsequent increases in yield.

3.4. Yield and quality

Yields of asparagus were influenced by cultivar, irrigation or their interactions in all years of the study (Table 4). Compared to the unirrigated control, overhead irrigation resulted in 10% greater mean cumulative yields for GM during the 2012-17 growing seasons, with the largest yield benefits (21%) occurring in spring 2012, following hot, dry conditions in summer 2011. JS yields were 7% higher in irrigated compared to unirrigated treatemtns in 2012, following drought conditions in summer 2011. However, in contrast to GM, JS yields were equal to or lower in irrigated compared to unirrigated treatments in subsequent years, and there were no cumulative yield benefits of irrigation. Yields of JS were approximately 13% lower in irrigated compared to unirrigated controls in 2017.

Variation in cultivar yield-response to irrigation has been observed in several other studies. For example, Wilson et al. (1996) found that the cultivar “Jersey Giant” was less sensitive to irrigation than “UC157”. Schaller and Paschold (2009) reported that “Gijnlim” was more susceptible to drought stress than “Grolim”. Rolbiecki and Rolbiecki (2007) also observed differences in cultivar response to irrigation with European cultivars generally showing greater positive response than non-European cultivars including JS.

The reason for the negative response of JS to irrigation observed in the last year of the study is unclear. One possibility is that irrigation resulted in excessive moisture in the crop root zone in irrigated treatments in some years. This may have occurred in late summer of 2015, when a late irrigation event was followed by rainfall, resulting in elevated VWC and near saturated soil moisture conditions in early fall (Fig. 2E). Wilson et al. (1996) observed yield reductions under high levels of irrigation in New Zealand, and speculated that the cause may have been late season fern renewal which depletes bud number and root carbohydrate storage, thus leading to yield reductions in the following year. Excessive moisture conditions may also have exacerbated soilborne fungal pathogens of asparagus including *Phythophthora* and *Fusarium* species (Falloon and Grogan, 1991; Saude et al., 2008).

3.5. Cultivar differences in water use

Changes in soil water content by depth during dry periods in unirrigated treatments were often different in JS compared to GM treatments (Fig. 3). Total changes in VWC in the top 90 cm of soil during drydown periods were greater in JS compared to GM treatments, especially during the 2013–2016 seasons, 4–7 years after establishment (Fig. 3C–F). Differences in soil moisture loss between cultivar

Table 4
Effects of irrigation and variety on yield.2012–2017.

Treatment	2012 T/ha	2013	2014	2015	2016	2017	Total 2012–17
Cultivar Main Effect							
Jersey Supreme	3.30 a	6.01 a	5.82 a	6.56	4.04	5.70	31.62
Guelph Millennium	2.99 b	5.32 b	5.13 b	6.92	5.14	6.74	32.41
Irrigation Main Effect							
None	2.92 b	5.49	5.40	6.61	4.65	6.32	31.56
Drip	3.24 a	5.74	5.62	6.84	4.42	6.18	32.22
Overhead	3.28 a	5.77	5.40	6.77	4.71	6.15	32.29
Cultivar*irrigation							
Jersey Supreme							
None	3.14	5.83	5.89	6.04 ab	4.42 bc	6.25 b	32.49 ab
Drip	3.43	6.17	5.91	5.84 ab	3.74 c	5.50 c	31.51 ab
Overhead	3.32	6.03	5.64	5.69 b	3.95 c	5.33 c	30.87 b
Guelph Millennium							
None	2.69	5.14	4.91	5.76 ab	4.88 ab	6.39 ab	30.62 b
Drip	3.04	5.30	5.33	6.38 a	5.08 ab	6.85 ab	32.92 ab
Overhead	3.24	5.52	5.16	6.39 a	5.46 a	6.97 a	33.70 a
ANOVA	P-value						
Cultivar	0.0028	< 0.0001	0.0002	0.0365	< 0.0001	< 0.0001	NS
Irrigation	0.0141	NS	NS	NS	NS	NS	NS
Cultivar x Irrigation	NS	NS	NS	0.0274	0.0100	0.0069	0.0641

1Within each column, different letters indicate signficant difference at $P < 0.05$.

treatments were largest at depths below 60 cm (JS greater than GM), likely reflecting greater rooting depth of JS compared to GM. For example, the percentage of soil moisture lost from 60 to 90 cm ranged from 23 to 27% of total soil moisture loss (from 0 to 90 cm) for JS, but only 8–17% for GM treatments. In contrast, the percentage of soil moisture loss from the top 30 cm ranged from 35 to 40% for JS, compared to 53–60% for GM.

Previous studies suggest that the effect of cultivar root depth on yield depends critically on the specific crop, soil type and climate conditions (Lopez et al., 2017). Although the effects of irrigation and

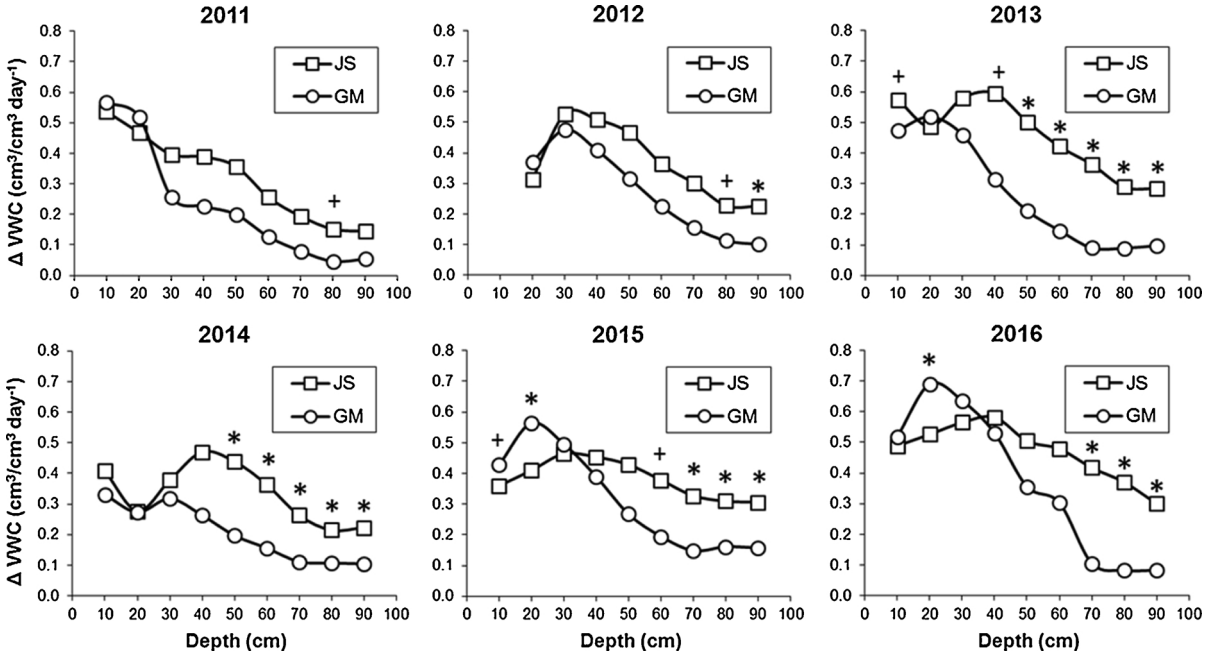

Fig. 3. Daily reduction in volumetric water content in unirrigated plots by depth (0–90 cm) and cultivar (JS = Jersey Supreme; GM = Guelph Millennium) during selected 1–2 week periods without rainfall: 11–24 July 2011; 25 June- 6 July 2012; 10–25 July 2013; 24–31 July 2014; 22–29 July 2015; and 2–8 August 2016. Signficant cultivar effects on soil moisture removal at specific depths are indicated by a "*" ($P < 0.05$) or "+" ($P < 0.10$).

tillage on asparagus root distribution have been characterized (Drost, 1999; Drost and Wilcox-Lee, 2000) to our knowledge, cultivar differences in asparagus water use by depth have not been previously explored. High root length density in deep soil layers has been associated with high yields during drought stress in other crops including chickpeas (Kashiwagi et al., 2006), and simulation models for sweet sorghum suggest that breeding aimed at increased rooting depth may be a valuable approach to reducing drought stress (Lopez et al., 2017). However, vigorous root growth can also deplete soil water reserves, resulting in reduced yields if subsequent drought stress occurs (Vadez, 2014; Lopez et al., 2017). In our study, JS removed moisture from deeper in the soil profile, but also generally removed more total soil moisture than GM (Fig. 3), suggesting that under extreme drought conditions with limited soil water reserves, JS could be less drought tolerant than GM.

4. Conclusion

Our hypothesis that irrigation during fern growth would improve asparagus yield under Michigan growing conditions was supported for the cultivar GM, but not for the cultivar JS. For GM, irrigation during fern growth in relatively hot, dry years, resulted in improvements in yield the following year. Over the course of the experiment, overhead irrigation resulted in a 10% increase in cumulative yields of GM, or the equivalent of 3.1 T ha^{-1}. In contrast, for JS, irrigation had little or no benefit beyond the first year, and resulted in yield reductions of as much as 13% in year 7.

One interesting result from our study was that variation in cultivar response to irrigation appeared to be related to differences in rooting depth as evidenced by differences in soil water loss patterns (Fig. 3). Under drought conditions, the deeper root profile of JS compared to GM may have facilitated drought avoidance by accessing deeper soil moisture pools. Although drought tolerance may be conferred through other mechanisms in asparagus (e.g. Schaller and Paschold, 2009), selection for more extensive root systems may be a useful approach for mitigating risks of drought stress without reliance on expensive irrigation systems (Lopez et al., 2017).

The highest yields recorded in our study (7 T ha^{-1} in 2017) were obtained with GM cultivar under overhead irrigation. In addition, GM is well-known for its greater stand-longevity under Michigan and Ontario growing conditions compared to cultivars closely related to JS (e.g. “Jersey Giant”), even when irrigation is not used (Panjtandoust and Wolyn, 2016). Therefore, given current cultivar choices, investment in irrigation appears to be an important practical strategy for mitigating risks associated with drought stress.

Overall, these results demonstrate the important potential role of both genetics and management practices in mitigating drought risk. They also illustrate the complexity of these interactions and potential tradeoffs associated with alternative risk mitigation strategies. Although JS was less dependent on irrigation to maximize yields compared to GM, it is also appears to be more sensitive to excessive moisture conditions, and hence potentially less reliable under the increasingly variable rainfall conditions predicted by climate models. Given projected increases in both the incidence of drought stress, as well as increases in periods of excessive moisture, selection of cultivars with drought tolerance may be counterproductive if they are correlated with disease-sensitivity.

To better understand such potential tradeoffs, identification of the underlying mechanisms associated with the indirect impacts of soil moisture on crops is needed. For example, excessive soil moisture during the late-fern growth stage may reduce subsequent yields by interfering with the optimal timing of dormancy induction, promoting counterproductive late-season fern initiation, or exacerbating soil borne fungal diseases. If the former, then plant breeding and management strategies to minimize this problem might focus on genetic control of dormancy induction (e.g. Panjtandoust and Wolyn, 2016). On the other hand, if the moisture response is driven by interactions with soilborne disease, then breeding efforts to identify disease tolerance traits are likely to be most beneficial. In either case, management practices which buffer asparagus from stress should be helpful if current climate trends continue. Such practices may include not only irrigation, but practices such as cover-cropping which may improve soil physical and biological properties that improve infiltration and water holding capacity. Other management practices which indirectly address issues associated with excessive or deficient soil moisture (e.g. integrated cultural and chemical disease management) will likely also be critical to maintain crop productivy in a changing climate.

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